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# Mysteries of the Indian Ocean Monsoon System

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**Abstract:** South Asian monsoon is an important part of global climate, affecting large areas of the Indian subcontinent. Monsoon is life and death to the people of South Asia as good monsoon is a boon to the farmers whereas an unusual monsoon can bring misery to the people through widespread floods and droughts. Strong differential heating of the Indian landmass and the latent heat released from precipitation mainly drive the present day summer monsoon circulation. During the northeast (winter) monsoon season, winds are dry and biological productivity in the northern Indian Ocean is low providing little food to the deep-sea. In opposition, the intense, wet, monsoonal winds of the southwest (summer) monsoon cause widespread upwelling and high surface productivity, thus a high supply of organic particles to the sea floor. During high surface productivity distinct fauna and flora flourish in the surface water column in various parts of the northern Indian Ocean. Study of these monsoon proxies accumulating in layers of sediment over hundreds to millions of years help understand the history of monsoons over various time scales. Recent study suggests a mechanistic link between the North Atlantic Ocean and the southwest monsoon at century-millennial time scales during the Holocene, suggesting importance of tropics and high latitude teleconnection. On short time scales monsoon variability has also been related to the Indian Ocean Sea Surface Temperature (SST), Himalayan-Eurasian snow as well as El Nino-Southern Oscillation (ENSO). This study reviews different aspects of past monsoon variability and its future implications.

**Keywords:** Indian Ocean, Summer monsoon, Biological productivity, Holocene, Monsoon proxies.

## INTRODUCTION

The South Asian region, including India, experiences seasonally reversing wind system – called the 'monsoon', which is an important component of the global climate. The monsoon system has often been called as the Indian monsoon, the South Asian monsoon, and the Indian Ocean monsoon, and is closely related to the African and East Asian monsoon systems. During summer (June-September) the South Asian landmass is warmer than the ocean, driving winds from southwest (SW) to the northeast towards the continent and are called southwest or summer monsoon. In winter (November-February) the pressure cells reverse and thus the winds blow from northeast to southwest forming the northeast or winter monsoon. The seasonal reversal of the Indian monsoons (Fig. 1) is one of the most spectacular features of Earth's climate system, affecting the weather pattern between 30°N and 20°S over the African, Indian, and Asian landmasses (Webster, 1987). Strong differential heating of the Indian Ocean and Himalayan-Tibetan Plateau, and the latent heat released from precipitation drive the summer monsoon circulation (Fig. 2). During the dry northeast (boreal winter) monsoon, biological productivity in the Indian Ocean is low providing little food to the deep-sea microorganisms. In contrast, the intense, wet, monsoonal winds of the southwest (boreal summer) monsoon cause widespread upwelling and high surface productivity in different parts of the northern Indian Ocean (Banse and English, 1994; Barber et al. 2001; Gregg, 2002; Gupta et al. 2003), thus a high supply of organic particles to the sea floor (Gupta and Thomas, 2003). Due to summer monsoon upwelling a variety of phytoplanktons and zooplanktons thrive in the Arabian Sea, some of them serve as good monsoon proxies (Prell, 1984; Gupta et al. 2003). Across the region, the effects of the monsoon are preserved in different proxies that include tree rings, soils, ice, lake deposits, cave deposits and marine sediments. Terrestrial sediments of several fresh water lakes provide a complement to the marine sequences.

The summer monsoon brings heavy rains over the Indian landmass whereas during winter monsoon season the precipitation is low. Agricultural practices have been developed to take advantage of the strong contrast between

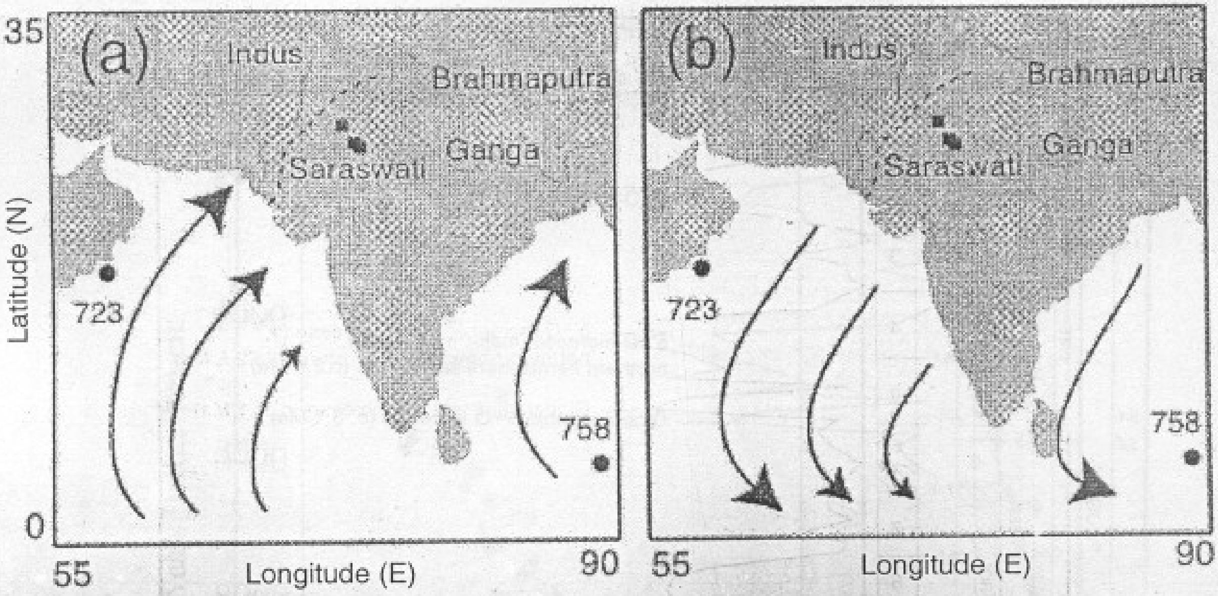


**Fig.1.** Reversing winds during (a) summer (July month), and (b) winter (January month) monsoon seasons.

the seasons. A good summer monsoon is a boon to the people of South Asian countries and their economy, but below normal monsoon can bring misery to people of the region. For example, a very strong summer monsoon may inundate low-lying areas due to torrential rains and floods, displacing people and rendering thousands homeless. On the other hand, a weak monsoon may cause droughts, triggering population migration to productive areas and affecting the socio-economic life of people of the region. Thus, monsoon is life and death to people of South Asia.

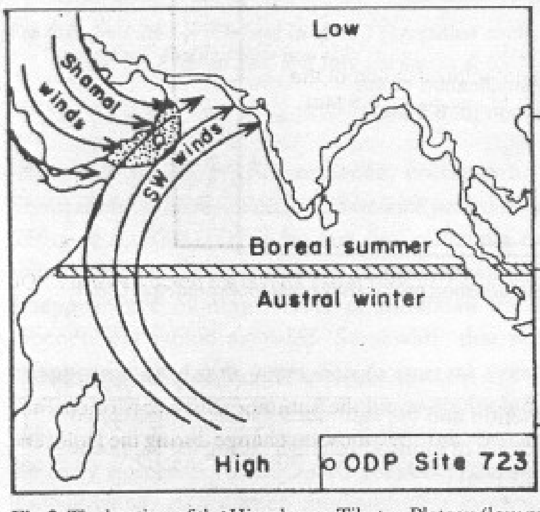


**Fig.2.** The heating of the Himalayan-Tibetan Plateau (low pressure) drives the southwest monsoon (Clemens et al. 1991). The strong southwest (summer) monsoon winds develop widespread upwelling zones in the northern Indian Ocean including off the coast of Oman leading to high surface productivity (Stippled area).

## EVOLUTION OF THE PRESENT DAY MONSOON SYSTEM

Indian Ocean climate dominated by monsoons has been strongly affected by the uplift of the Himalayas and Tibetan Plateau (Molnar et al. 1993; Prell and Kutzbach, 1997), leading to the initiation of the South Asian monsoons in the late Miocene ca 10-8 Ma (Fig. 3; also Kroon et al. 1991), with a peak in monsoonal intensity at about 5 Ma (Gupta and Srinivasan, 1992; Takahashi and Okada, 1997; Wang et al. 2000). Another important change in the monsoon behaviour occurred when seasonality increased ca 3.0 Ma as recorded in deep-sea benthic foraminifera (Gupta and Thomas, 2003). Prior to this time, benthic foraminifer species indicative of a large seasonal cycle in the surface ocean are reduced in abundance. The increased monsoon seasonality during the mid-Pliocene is coeval with the initiation of major Northern Hemisphere (NH) continental ice sheets and uplift of the Himalayas-Tibetan Plateau (Zheng et al. 2000; Zhisheng et al. 2001).

While the long-term changes in the monsoons have been linked to the Himalayan-Tibetan uplift (Zheng et al. 2000; Zhisheng et al. 2001) and the NH glaciation (Gupta

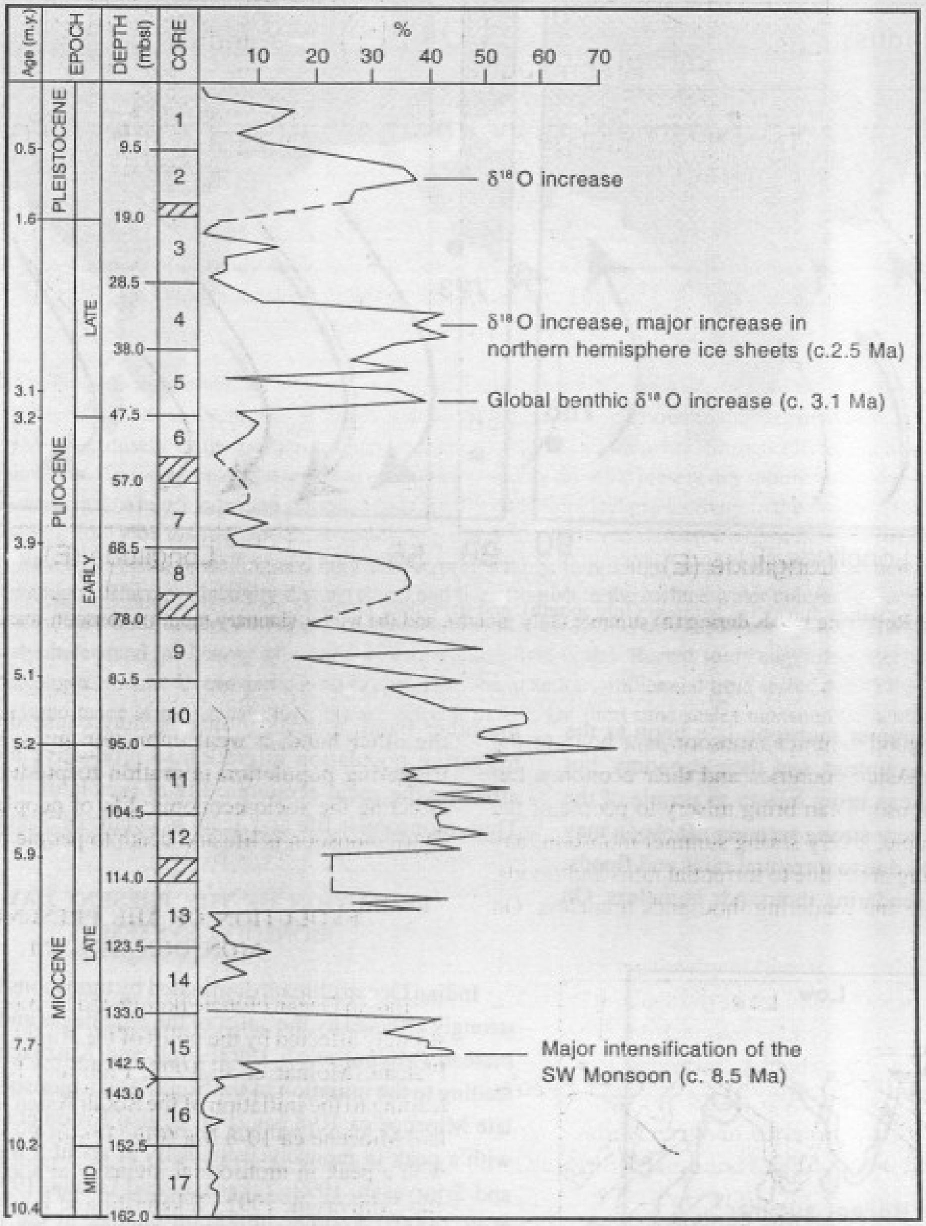


Fig.3. Beginning of present day Indian monsoon system ~8.5 Ma based on a southwest monsoon proxy *Uvigerina proboscidea* at DSDP Site 214 (modified from Gupta and Srinivasan, 1992).

and Thomas, 2003), century and millennial scale changes have been attributed to changes in the North Atlantic and in Eurasia where the extent of winter snowfall influences the monsoon the following summer (Schulz et al. 1998; Anderson et al. 2002; Gupta et al. 2003). Changes in the monsoons are also related to the orbital cycles in eccentricity, tilt, and precession, changing slowly over thousands of years (Gupta et al. 2001). For example, the slow change in the precession of the earth's axis of rotation, changing the timing between perihelion and the summer solstice, is often cited as a principal cause of monsoon change during the Holocene (Clemens et al. 1991).

## MONSOON VARIABILITY AND POPULATION IN SOUTH ASIA DURING THE HOLOCENE

Human settlements and migrations have been closely related to climate variability throughout the known records

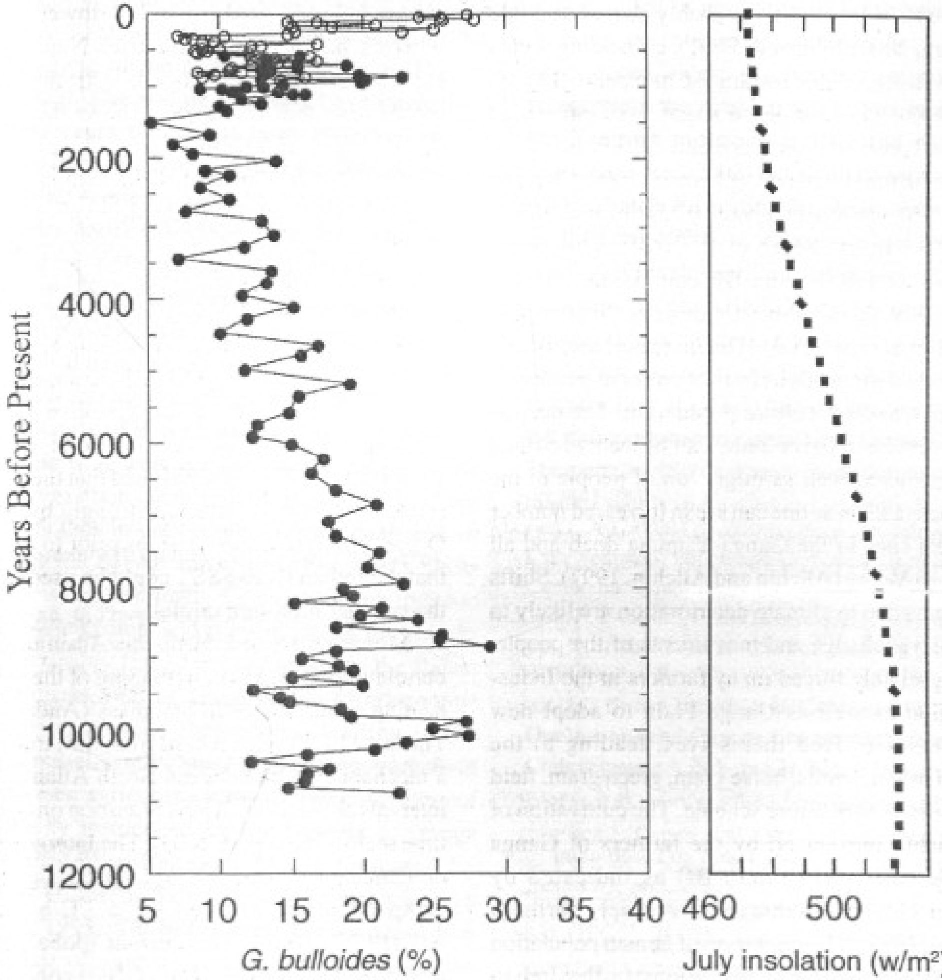


**Fig.4.** *G. bulloides* percentage in Hole 723A (filled circle; Gupta et al. 2003) and box core RC2730 (open circle; Anderson et al. 2002) from the Arabian Sea, and July insolation at 65°N (Berger and Loutre, 1991).

(Nunez et al. 2002). For instance, collapse of Maya Civilization has been linked to an extended period of drought (Haug et al. 2003). Over the last few millennia extreme changes in the monsoons have caused appearance and disappearance of major river channels in the Indian subcontinent including river 'Saraswati' that probably disappeared ca 4,000 years before present (years BP) (Radhakrishna, 1999). Several major rivers including the Indus and Saraswati were running in their full vigour during the early Holocene 10,000-7,000 years BP (Singh, 1971; Radhakrishna, 1999) when the southwest monsoon was much stronger than today (Gupta et al. 2003). Archeological evidence suggest a link between southwest monsoon variability and the development and migrations of human civilizations in the Indian subcontinent (Singh, 1971). Summer insolation was about 8% greater, and winter insolation about 8% less than today at the beginning of the Holocene leading to a greater contrast between the seasons (Berger and Loutre, 1991). The interest in agriculture practices increased in the early Holocene with wheat and barley (winter, *Rabi* crops) as major crops. It is likely that the summer monsoon wet season was longer in the early Holocene, and the precipitation more than required for summer food production, providing enough moisture for winter crops. The excess moisture source and/or longer summer monsoon season in the early Holocene might have caused widespread floods and that probably did not allow early farmers of the Indus-Saraswati region to grow *Kharif* (rainy season) crops like maize, millet (*jawar, bajra*) and a variety of lentils. These crops were probably introduced later with the beginning of arid phase in India.

The arid phase in South Asia probably started ca 5,000 years BP (Singh, 2002; Maxwell, 2001), coinciding with a stepwise weakening of the southwest monsoon (Fig. 4; Gupta et al. 2003). The arid phase might have intensified ca 4,000-3,500 years BP as has been observed in the terrestrial record in the Himalayas (Phadtare, 2000; Chauhan and Sharma, 1996), western peninsula (Caratini et al. 1994), and northwestern India (Singh et al. 1990). This phase probably ended ca 1,500 years BP coinciding with the weakest interval of the southwest monsoon (Sharma and Gupta, 1997; Gupta et al. 2003). The increased aridity and or drying phase had tremendous impact on socio-economic life of population and agriculture production. The decline in rainfall and demise of River Saraswati probably resulted in local adaptations as well as migration of people to the east towards Ganga Plain as one can see in increased number of archeological sites in the Ganga-Yamuna doab and all across the Ganga Valley (Allchin and Allchin, 1997). Shifts in fluvial systems due to climate deterioration are likely to cause the life-style change and movements of the people. The dry spell probably forced many farmers in the Indus-Saraswati region as well as Ganga Plain to adopt new farming strategies to feed themselves, leading to the introduction of millet, lentils, horse gram, green gram, field peas, etc. in the new agriculture scheme. The cultivation of rice was probably introduced by the farmers of Ganga Plain in the second millennium BC as indicated by excavations at Hulas in Saharanpur district, northern India (Saraswat, 1993). The migration of human population and rise and fall of various civilizations in the Indian subcontinent thus are closely related to the monsoon, which continues to be a part of daily ritual to people of the Indian subcontinent as it has been over the last several thousands of years.

## SOUTHWEST MONSOON - NORTH ATLANTIC OCEAN LINK, RECENT FAILURES AND FUTURE IMPLICATIONS

Meteorologists are trying to understand whether current monsoon failures in some parts of South Asia and intensifications in other parts are related to increased global warming. Monsoon records in many areas are not significantly correlated with all-India rainfall data due to large inter-regional variability in Indian rainfall (Shukla, 1987). This has been the case in the year 2002 when summer monsoon was delayed in eastern and southeastern parts and almost failed in northern and northwestern parts of India, whereas neighbouring countries Nepal and Bangladesh experienced widespread floods. Last millennium monsoon record from the Arabian Sea shows increased intensity of the summer monsoon during the past four centuries (Anderson et al. 2002) but all-India monsoon rainfall shows a little change supporting the observation by Shukla (1987). By the early 1900s, monsoon workers identified two major forcings: Himalayan/Eurasian snow cover and the El Niño-Southern Ocean (ENSO) cycle, but the last 140-year historical data suggests a weakening relationship between the Indian monsoon and ENSO (Kumar et al. 1999). More recently, Li et al. (2001) found a positive correlation between the Indian monsoon rainfall and Indian Ocean Sea Surface Temperature (SST). They argued that the summer monsoon rainfall seems to be affected strongly by equatorial Indian Ocean SST, one to two seasons prior to the monsoon, such that the Indian Ocean SST could be used as a precursor for the summer monsoon rainfall.

Monsoon record from the Arabian Sea suggests a correlation between strengthening of the SW monsoon and heating of the Eurasian landmass (Anderson et al. 2002). The last 11,000 years record from the Arabian Sea suggests a mechanistic link between North Atlantic cold spells and intervals of weak southwest monsoon on century-millennial time scale (Gupta et al. 2003). The Intergovernmental Panel on Climate Change (IPCC) projects a global Surface Air Temperature rise between 1.4°-5.8°C by the end of 2,100 AD (IPCC, 2001). The current global warming due to increased Green House Gas (GHG) concentration appears to intensify the southwest monsoon in future as we have observed over the past four centuries (Anderson et al. 2002). But global warming may eventually have a negative feedback, when increasing fresh water discharge from Eurasian Arctic Rivers to the North Atlantic either blocks or slows down the global conveyor (Rahmstorf, 2002; Broecker, 1997). The slow/shut down of the conveyor or North Atlantic Deep Water formation may trigger a cooling phase if not a full ice age and thus a weak southwest monsoon (Gupta et al. 2003) in the coming decades. Thus it is important to increase our understanding of the land-ocean interaction and arctic hydrological cycle for better monsoon predictions.

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